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Fluid-structure interactions and flow induced vibrations: A review

R. Parameshwaran[a,*], Sai Jathin Dhulipalla[a], Daseswara Rao Yendluri[a]

[a] *Department of Mechanical Engineering, Birla Institute of Technology and Science – Pilani, Hyderabad Campus, Hyderabad, India – 500078.*

Abstract

Fluid-structure interaction (FSI) is intensely coupled with the flow induced vibration (FIV) through the motions induced on a deformable or moving structure being subjected to an external or internal fluid flow. This kind of interaction in turn evolves with a variety of flow phenomena having applications that ranges from aeroelasticity to blood flow through arteries. The prime objective of this paper is to review the potential research studies pertaining to a variety of modelling and computational techniques, dedicated for exploring the underlying physics of the phenomena relating to the fluid structure interactions and the flow induced vibrations. Technical revelations related to the dynamic effects of the flow induced vibrations on engineering systems in fluidic environment have been gleaned from numerous research studies and presented. Emphasis is also given on the fluid flow analysis pertaining to the excitation of low-frequency vibration modes in structures at nanoscale for the efficient design of modern engineering systems.

Keywords: Finite element analysis; Kinetic and elastic energy; Fluid-solid interface; Molecular dynamics simulation; Viscosity.

1. Introduction

In recent years, the interests towards the sophisticated development of engineering systems based on the fluid structure interaction and flow induced vibrations have been gaining momentum. Basically, fluid structure interactions refers to the interaction experienced between the structure of flexible in nature and the fluid surrounding the structure. This type of interaction is very interesting from the standpoint of applications including modeling and design of aircraft wing structures, components of turbomachines, design and construction of bridges, blood flow analysis through the arteries and so on. Another reason for implementing the FSI analysis into the engineering and

* Corresponding author. Tel.: +91 40 6630 3665; fax: +91 40 66303998.
E-mail address: parameshwaranr@hyderabad.bits-pilani.ac.in, parameshviews@gmail.com, jathin57@gmail.com, yvdrao@hyderabad.bits-pilani.ac.in

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biological systems could be because of its inherent attributes related to the simulation of the rigid/flexible structures which are geometrically complex in nature, and which are prone to large deformations with respect to the fluid flow.

Pipe systems conveying fluid are prevalent in many fields including marine and civil engineering, nuclear and electric power industries, petroleum and chemical process industries, ship, aircraft applications, human veins and other areas of daily life. Deformation of a flexible solid structure occurs due to the induced pressure by the flowing fluid either inside or outside. Structure in turn causes a change in fluid pattern, which leads to further change in pressure on the structure and this process is repetitive. For instance, fluid flowing past the air plane wings causes deformation of the wings which causes change in the airflow pattern around the wings. Fluid structure interactions cause failure of stationary structures under fluid flow conditions or moving structures in stationary fluid. The surrounding fluid increases the effective mass of the structure like a movement of pendulum in a fluid. In this paper, potential research contributions pertaining to the FSI and FIV analysis for the real time applications have been gleaned and presented. Emphasis is also made on the micro and nanoscale level structures undergoing fluidic interactions and induced vibrations.

2. Fluid Structure Interaction (FSI)

A flow oscillator model usually has two mechanical oscillators – one for modelling structural oscillations and a non-linear model representing fluid behaviour paired to structural motion which is a reduced order mechanical model, making it a subclass of physical model [1]. This is helpful as an analytical model to nonlinear fluid structure interactions related to offshore structures. This can be further extended (when using Hamilton principle based variational principle) to problems of more complex nature with higher degrees of freedom if generalized equations can be obtained as a super set of flow oscillating models. Relevant dynamic equations have been derived for fully coupled interactions of a stationary cylinder as well as with transverse degree of freedom in uniform viscous flow. These are being extended into more practical systems by considering two degrees of freedom for rigid cylinder and modelling the structure as an elastic body.

During transient phases in pipe flow (particularly liquid filled) systems, significant Fluid Structure Interactions (FSI) may occur and need to be carefully dealt with. When fluids flowing in pipes are abruptly forced to stop or change direction, pressure surges occur – commonly referred to a waterhammer [2]. Waterhammer can lead to high pressures as well as low pressures. Low pressures might potentially lead to pipe collapse particularly in the case of underground pipelines leading to cavitation. Structural dynamics and static pipe stress analyses provide an insight into reaction forces and resonance frequencies. In conventional waterhammer analyses, pipe elasticity is considered along with propagation speed of pressure waves, which works quite well unless the pipe is not rigidly anchored. In such situations, pipe inertia and axial motion come into play and dynamic behaviour of fluid and pipe system are required to be dealt with simultaneously. Depending on basic equations one dimensional FSI models can be classified depending on number of first order partial differential equations with increasing number of equations taking more parameters into consideration. A fourteen equation model which describes longitudinal, flexural and torsional motion in thin walled pipe systems is sufficient for almost all practical purposes but it can be improved with flexibility and stress intensification factors to take effects like elbow ovalization effects into consideration and with concreted cavity model to account for column separation as well as vaporous cavitation. Higher dimensional models are required only when high accuracy is needed.

Numerical studies on the interaction of fluids with solids especially in partially filled containers is extremely important owing to the fact that liquid motion in containers finds applications in various fields of engineering like naval construction, airspace vehicles, automotive engineering as well as in dam breakage problems [3]. In this aspect of discussion, sloshing phenomenon (described as highly non-linear movement of liquid free surface inside tanks [4]) which generates dynamic loads on tanks, particularly in vehicles generates a significant problem which could have adverse effects when combined with resonance [5, 6]. Though there are various numerical models proposed to model sloshing, finite element, finite difference and smoothed particle hydrodynamics methods are used widely and all three of them show good agreement with experimental data. Although these methods are being employed for analysis in various fields, application to complex and realistic container shapes is yet to be explored and developed further. Also, studies involving effect of slosh damping mechanisms like variable aperture flexible baffles are of major interest.

Interactions of fluids with flexible structures is important in application to stability analysis of aeroplane wings, blood flow through arteries and like. To study such phenomena, the task is to choose suitable fluid models (Computational Fluid Dynamics) and structural models (Computational Structural Dynamics) depending on the application and to develop an efficient interface to couple them which gives rise to Computational Aeroelasticity (CAE) [8, 9] as, the present models which approach computational aerodynamics and structural dynamic subsystems independently seem to be filled with complications [7]. This is due to the fact that CFD uses Eulerian coordinate system while CSD employs Lagrangian coordinate system along with time scales which could be very different for the modules making them quite different which prompts to develop an appropriate interfacing technique between them.

One specific phenomenon is the dip as the flutter velocity can be calculated based on it. Linear analysis using transonic small disturbance model (CAP-TSD) maybe used to obtain flutter boundaries in subsonic and ultrasonic range but in transonic range, viscous effects to the model have to be applied (CAP-TSDV) [10] to increase predictive accuracy which would otherwise be under conservative as highly non-linear effects come in to play which causes wings to undergo unsteady flexible motion. Flutter boundary could be determined by using viscous or inviscid analysis while using non-linear models. Inclusion of viscous effects [11-13] was more accurate in predicting transonic dip while significant improvement can be observed for supersonic regimes. Of the major three models of coupling, namely fully coupled model, loosely coupled model and closely coupled models, of which closely coupled model is one of the most widely used. It can be safely stated that it is an efficient and accurate way of coupling fluid and structural modules. Further, developing higher order aeroelastic models with detailed structure modelling and separated flow effects is to be developed now that Reduced Order Modeling (ROM) technique used to accurately model larger systems is gaining momentum.

Progress in micro technology has made mounting of surveillance equipment on small flying machines known as Micro Air Vehicles (MAVs) which have wing spans less than 15 cm and mini Unmanned Air Vehicles (UAVs) which are slightly larger [14]. Generating required lift and thrust forces at these dimensions and low Reynolds numbers (103 – 105) cannot be addressed by conventional methods [15-18]. Hence wing flexibility which is considered undesirable for conventional aircrafts can be exploited here to create periodic excitation of separated flows by oscillating wings that can delay stall and increase lift coefficient. To study the behaviour, rigid air foils in forced plunged motion are considered and lift enhancement achieved by deflected jets and convected Leading Edge Vortices (LEV). In the former method, deflected jets at high Strouhal numbers (parameter which depends on chord length) are created by pairing clockwise and counter clockwise Trailing Edge Vortices (TEVs) are create dipoles which causes wings to move to a certain angle with freestream inducing asymmetry in the flow field causing high lift coefficients (almost 6) in case of pre stall angles of attack. In the latter at low Strouhal numbers and post stall angles of attack, LEVs are formed on upper surface and convect over it creating a low pressure region generating lift with coefficient approximately proportional to plunging velocity.

When considering pipe flow in carbon nanotubes (CNTs), by using references in Fluid Structure Interactions (FSI) and established principles, it has been shown that viscosity of fluid flow is not present explicitly in equation of motion which allowed the development of a model for coupled vibrations undergone by CNTs carrying fluids using slip regime of fluid flow near walls and size dependent continuum theories [19]. The critical fluid flow velocity where instability occurs predicted by this model is greater than the average critical flow velocity predicted by plug flow theory which does not consider slip boundary conditions suggesting CNT conveying nano-flow could be in fact more stable than previously expected [20]. However, as the Knudsen number increases, this theory approaches plug flow theory and both would provide the same results. By considering various size dependent continuum theories and Knudsen number (Kn), it has been observed that Kn has a greater influence over critical flow velocity compared to size dependent parameters. In nano-flow Kn nullifies the effect of nonlocal parameters but for gaseous nano-flow, Kn increases the parameters making the critical velocity value similar to the predictions obtained FSI equations based on plug flow theory and other classical theories.

When fluid flow and elastic structure at nanoscales are investigated simultaneously using nonlocal continuum theory and Knudsen number (Kn) applying Euler-Bernoulli plug flow theory, results suggest that nonlocal parameter has greater effect on reduction of critical velocities compared to Kn for liquids [21]. However, for gas flows Kn cause more reduction in critical flow velocities. For both clamped-clamped and pinned-pinned boundary conditions effect of Kn was the same and slip condition on liquid nano-flow was not an effective parameter as far as continuum flow regime is concerned. Further, nonlocal elasticity had more influence on flow behaviour compared to effect of Kn especially in clamped-clamped system than in pinned-pinned system. However, in gas nano-flows Kn had greater influence in reducing critical velocities than dimensionless nonlocal parameter. Moreover in flows through nano-pipes, it has been observed that neglecting small size effects on nano-pipe could lead to non-conservative designs of fluidic nano-devices.

In electromechanical devices at nanoscale, deformation or vibrations result in mechanical operations [23]. In nanofluidic devices manipulation and precise control of fluids has to be achieved at molecular level [22]. At such dimensions, solvent molecules close to walls behave differently than the bulk phase due to interface and cohesion. At nanoscale, water travels at speeds close to its thermal velocity [24] (almost 100 m/s at room temperature) at inner wall of carbon nanotube resulting in drag forces in order of gigahertz and hence coupling between fluids and structure needs to be in place. Since for nanometre scales Reynold's is extremely low, Stokes approximation simplifies the Navier Stokes equation. It is found that at low speeds of less than 100 m/s, Stokes law gives an accurate enough estimation of flow resistance around a carbon nanotube but at higher speeds local heating occurs, weakening drag force an effect which cannot be captured by CFD techniques. This modelling suggests limitations in high speed applications of nano-structural devise. However, it also opens up the possibilities of tapping kinetic and elastic energies of microstructures.

Modelling a cardiac cycle consisting of flexible heart valves with realistic geometry and material parameters is highly complex as it should associate large rotations, translations and valve deformations [25]. To mimic valve closure, a contact algorithm needs to be incorporated and then interaction between blood and valve is to be considered. Starting with Immersed Boundary Method [26], extensive adaptation of research lead to finally introducing local fluid mesh adaptation [27] which does not keep its topology constant anymore by adapting fluid mesh to the solid's position. Finite element meshes of fluid and solid and liquid are generated separately and then couple using a Lagrangian multiplier along solid boundary. Though situations analogous to systole and diastole are coming up, a combination is still not possible. The computational time for 3D computation is very large as well, forcing a compromise in mesh resolution. There is a need to develop appropriate solver and more effective way of meshing.

Numerical simulations have the potential to retrieve detailed data on human mitral valve which could go a long way in developing medical therapies and surgical procedures. To model the complex geometry, vivo Magnetic Resonance Imaging (MRI) data is used to generate the human mitral valve model of considerable anatomical accuracy [28]. Dynamic modelling is challenging due to large deformations and anisotropic nonlinear elastic behaviour of valvular tissue and pulsating haemodynamic loads during cardiac cycle. When Immersed Boundary (IB) method which accounts for fluid structure interaction between blood flow and MV leaflets is used dynamic behaviour of chorded polyurethane mitral prosthesis provided results that showed much larger oscillations compared to clinical data. It could have possibly be due to pressure loading which is not realistic enough [29]. Considering kinematics and anisotropy of valvular tissue could possibly lead the model closer to reality [30, 31].

A cell activation base model inspired by cardio electro physiology has been developed to study large scale kinematics of endocardium [32]. Left Ventricle wall motion has been used to drive a large scale FSI between blood flow and leaflets of a bi leaflet mechanical heart valve (BMHV). The model produced positive results during systole and diastole but during valve closing phase the complex geometry and three dimensional retrograde flow coming from aorta induced highly asymmetric kinematics. The transmembrane potential which was used to drive the LV wall motion could be calibrated to imitate healthy or diseased hearts. The model could be further extended by considering smaller arteries around LV by taking patient specific data into consideration. This model could be taken closer to reality by considering the effect of flow from smaller arteries like carotid arteries, subclavian arteries etc. by incorporating one dimensional resistance models [33].

In any manufacturing industry, and particularly in microelectronic industry on which the whole world relies on, product reliability and quality are of utmost importance. Integrated circuit (IC) package design along with material selection immensely influence life of microelectronics [34]. Rather than relying on trial and error method, cost can be greatly influenced by using virtual modelling techniques to study the interactions between epoxy molding compound (EMC) and package structures like IC chip, solder bumps etc., to eliminate undesirable problems like voiding, delamination, cracks and fractures. The development of CAE and CFD made it possible to study problems such as flow front advancement in IC encapsulation, wire bonding deformations and material flow behaviour which would greatly reduce cost and time spent on research ahead of mass production.

Coupling in FSI analysis for IC encapsulation could be done using de-coupling method (which conduits fluid and structural analyses individually) or real-time coupling method (analyses of fluids and structure is combined) each of which have their own merits and demerits. Though FSI analysis for IC packaging provides a great detail, there is an ever growing need to evolve current techniques as microelectronics are beginning to advance into nano realm which will further add to the complexity of IC packaging, and computation.

3. Flow Induced Vibrations (FIV)

Section Flow induced vibration or sometimes referred to as the vortex induced vibrations (VIV) are the motions being induced on structures or rigid bodies, which is caused at the cost of the body upon interacting with a flowing fluid (external flow). Many research works pertaining to the studies on the FIVs or VIVs for the real time applications have been reported, in recent times. Lab-on-a-chip systems could be revolutionary owing to their size, low cost for fabrication, portability, and low sample waste volume consumption. Nanomaterials and microbeads are one of the tools which may help in developing advanced microfluidic analytic devices [35]. Magnetic nanoparticles (MNPs) are one class of nanoparticles which provide a great advantage as they can be easily manipulated and positioned [36]. One example of MNP applications that they have been used along with glucose oxidase to in enhancing signals of sensors by packing them tightly. Gold nano-particles (AuNPs) are other nanoparticles which are being experimented on for economical exploitation of properties [37]. Carbon nanotubes (CNTs) have many desirable features like high carrier mobility, mechanical flexibility and low production costs [38, 39]. Micro-channels are extremely useful to lab-on-a-chip technology as they can handle extremely small volumes of liquids along hundreds of micrometres.

As good as they seem in theory, majority of these concepts have not been applied practically. Their applicability is still questionable as they were tested using controlled and limited conditions. When dealing with such dimensions, there is high chance that complexities arise during fabrication. This combined with expensive raw materials which can negate the main advantage of cost reduction make mass production of devices far fetching. There is ample research developed on dynamics of pipes carrying fluid. To extend the research to vibrations of microscale pipes, equations of motion have been modified to accommodate for size effects [40]. To study flexural vibrations of micro-flow and micro-structure, two additional parameters, one associated with flow velocity profile and another material length scale parameter representing the size effect of micro-structure have been chosen which are valid for both straight and curved pipes. For straight pipes of various cross-sections, examining the lowest natural frequencies suggested that material length parameter and flow velocity profile parameter acted against each other. The material length parameter tends to stiffen the pipe causing an increase of critical mean flow velocity while flow velocity profile parameter tends to decrease the critical mean flow velocity. For curved pipes with clamped-clamped ends, conventional inextensible theory predicted a divergence similar to the case of straight pipes, but modified inextensible theories predicted that no instability is possible.

In two phase flows involving multiples metallic particles, particles experience high speed compressible forces that cause deformation and plasticity effects [41]. The presence of metallic particles also have influence on flow conditions and the particles they collide with [42, 43]. Plasticity effects undergone by the particles due to high speed compressible gas and particle flow can be incorporated into direct particle model in which soft collision model and safety zone technique are exploited to deal with particle collisions. For this purpose, fluid independent finite element model analysis of two colliding bodies is required and a range of colliding velocities are studied [44] in the system of fourteen steel particles and gas driven piston. Results have been obtained by developing the model using a two body (steel) collision system and then applying to the actual system required at different driving pressures. The results clearly indicated that the particles in this model attain a formation which is comparatively compact than in case of elastic perfectly plastic collision force model. The drawbacks of the technique lie in the fact that for each system, the collision effect model needs to be generated specifically and by using rigid body motion, deformations are not taken into account. To maintain mesh topology, details of particle deformation have not been modelled.

These problems might be overcome by coupling finite element analyses to fluid flow model as an attempt to make collision effect forces, deformations and particle motion internal to the simulation.

Nonlinear equation of motion based on Hamilton's principle and modified couple stress theory have been derived to study nonlinear free vibrations induced by micro-flows [45]. Modified couple stress captures the microstructure dependent size effects at micron and sub-micron levels. From this, efficient analytical expressions for post-buckling configuration, nonlinear frequency and response are obtained. Results showed that nonlinear natural frequencies decreased with outer diameters of micro-pipes and are always higher when compared to linear natural frequencies. However, Poisson's ratio did not signify any change in vibrational frequency. These analytical solutions could be applied for precise control of micro-fluid delivery.

Considering small size effects of nano-flow fields, FSI models can be improved for studying CNT structural dynamics. Nanotube used in simulation has been modelled by Euler Bernoulli plug flow beam kinetic theory considering slip boundary conditions of nano-flow. Results from the model showed that velocity gradient over nanotube walls was lower compared to that estimated by using continuum flow theory with no slip conditions[46]. In case of nano-gas flows, slip boundary conditions showed remarkable effects but in case of nano-liquid flows they were not so influential. Small size effects on flow field reduced the flow shear which deteriorated effective viscosity. Considering this, viscosity effects need not be considered for nanotube conveying viscous fluids at fundamental frequencies. Small size effects also lowered damping ratio. This suggested that when small size effects are considered, viscosity played little role in stabilizing the system. It has also been concluded that nano-gas flow was more dependent on small size effects than nano-liquid flow.

Thermal properties of fluid confined in FCC lattice nano-channels is investigated by using non-equilibrium molecular dynamics in which a ratio is considered to describe fluid-lattice interactions based on wall parameters [47]. It has been found that fluid showed different wettability at lower temperature ranges on fluid wall surfaces. When the ratio is small, lattice results in small wall attractions and the number of particles absorbed decrease. The fluid particles have been observed to move closer to the wall. As the temperature increases, these effects will be supressed. This is observed due to Kapitza resistance [48, 49] generated by fluid wall interactions. When temperature increases, atoms get enough energy to break through wall interactions and behave as bulk flow. The fluid properties are controlled by wall interactions as well as temperature.

Microfluidics promise a great deal of advantages in the field of drug discovery like low sample consumption and analysis or experiment times [50]. Like any other technology, to be able to implement microfluidics [51, 52], suitable production techniques have to be discovered and cost of production must be optimized. Microfabrication which spawned out from microelectronic industry making use of glass and silicon. The drawback was in the high final costs of due to materials and process of production. Fabrication is usually done by micromachining on glass or silicon or micro replication. The latter methods are comparatively are economical compared to the former as the reference templates can be reused to produce many replicas. Microfluidic systems can have various applications in drug discovery like automated electrophysiology, proteomic applications, micro-parallel liquid chromatography and protein crystallization. There are many fabrication techniques which are suitable for production of microfluidic systems but the future could hold the key to implementation.

Vascular cell biology is a field in which extensive research is being carried out due to its relevance in biomedicine. The main obstacle is that it is difficult to mimic the functioning of valve tissue [53]. Microfluidics shows great potential to enable a systematic study of vascular cell biology. Firstly, the materials required for research related to vascular biology are hard to obtain and extremely expensive which force research to be carried out using extremely low quantities of material. Microfluidics could be an excellent choice to handle low quantities. Vascular endothelial cells are highly responsive to shear stress caused by fluids flowing over them, a response shared by microfluidic devices. These provide for excellent study models to gain better understanding of vascular tissue without the need for expensive research material. In microfluidic channels, flow velocities are small resulting in low Reynolds number due to which only laminar flows persist preventing mixing of fluids. This allows multiple parallel flows in a single microfluidic channel with sufficient time for particle exchange through diffusion. Multiple parallel flow can be exploited in various applications like patterning cells inside microfluidic device or three dimensional culturing. Microfluidic setting can also be used to setup desirable biological environment like in studying stem cells. Microfluidics is however still in early stages of development and will require much research before it can be applied on commercial level.

4. Conclusion

In summary, from the perspective of the research outcomes presented here, the usefulness of the FSI and FIV analysis on the flexible/rigid structures dedicated for the real time applications were much encouraging, and has signified the potential opportunities and scope available to explore and improvise the features of such structures in the imminent future.

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